Milli-Hertz and Giga-Hertz Gravitational Waves

Mike Cruise
University of Birmingham
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Context

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• The frequency of these gravitational waves will therefore be in the range
  – 50 Hz- 3 kHz, or
  – About $10^{-8}$ Hz
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- About $10^{-8}$ Hz

Both these detection methods are sophisticated, sensitive and funded.
On the Other Hand
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- Gravitational waves, by similarity to electromagnetic waves, exist at all frequencies and studying them at different wavelengths will permit observation of different cosmic objects or different emission processes.
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- The low frequency detectors are the result of much work by the LISA Team across the world (US, Germany, Italy, UK, France, Spain, Switzerland).
- The high frequency work has been done at Birmingham.
• A principal motivation for going to low frequencies is to access the radiation expected from super massive black holes and galactic binary systems. $F \sim 10^{-3}$ Hz
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This requires a space mission
LISA

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- Low frequencies imply long arm lengths $L \sim 5 \times 10^9$ m
- This requires a space mission
Basic LISA Concept: Sensitivity
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Measure 10 pm change in 5 million Km
Basic LISA Concept: Sensitivity

Measure 10 pm change in 5 million Km

\[ h \sim \frac{10^{-11} \text{m}}{5 \times 10^9 \text{m}} \sim 2 \times 10^{-21} \]
Basic LISA Concept: Sensitivity

Measure 10 pm change in 5 million Km

\[ h \sim \frac{10^{-11} \text{m}}{5 \times 10^9 \text{m}} \sim 2 \times 10^{-21} \]

Do this for a year and reach \( h \sim 10^{-23} \)
Signals from SMBH’s
Signals from SMBH’s
Signals from SMBH’s
Signals from SMBH’s

Gravitational Wave Amplitude $h$

S/C motion

MBH-MBH Binaries at $z=1$

LISA Instrumental Threshold
1 yr, S/N=5

Binary Confusion Noise Threshold Estimate;
1 yr, S/N=5

Frequency (Hz)
Signals from SMBH’s

- S/C motion
- Shot noise
Signals from SMBH’s

- S/C motion
- Shot noise

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Signals from SMBH's

- S/C motion
- Shot noise
- Arm length

Frequency (Hz)

Gravitational Wave Amplitude $h$

$10^7/10^8 M_\odot$

$10^8/10^9 M_\odot$

MBH-MBH Binaries at $z=1$

LISA Instrumental Threshold
1 yr, S/N=5

Binary Confusion

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## Galactic Binaries

- **resolved systems**

<table>
<thead>
<tr>
<th>Type</th>
<th>birth rate (yr(^{-1}))</th>
<th>resolved systems</th>
<th>with frequency change</th>
</tr>
</thead>
<tbody>
<tr>
<td>(wd, wd)</td>
<td>(2.9 \times 10^{-2})</td>
<td>12163</td>
<td>560</td>
</tr>
<tr>
<td>AM CVn</td>
<td>(1.8 \times 10^{-3})</td>
<td>10117</td>
<td>49</td>
</tr>
<tr>
<td>UCXB</td>
<td>(9.0 \times 10^{-5})</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>(ns, wd)</td>
<td>(1.4 \times 10^{-4})</td>
<td>21</td>
<td>3</td>
</tr>
<tr>
<td>(ns, ns)</td>
<td>(3.2 \times 10^{-5})</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(bh, wd)</td>
<td>(3.8 \times 10^{-5})</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(bh, ns)</td>
<td>(1.0 \times 10^{-5})</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>22340</td>
<td>614</td>
</tr>
</tbody>
</table>

---

*Sils Nelemans*
Galactic white dwarf binaries

LISA is expected to provide the largest observational sample of white dwarfs (WDs)

- Very large number in frequency space

![Graph showing log f (Hz) vs log h]

$$\frac{dN}{df} = 2 \times 10^8 \, \text{Hz}^{-1} \left( \frac{0.001 \, \text{Hz}}{f} \right)^{11/3}$$

WDs are detected as

- Individual deterministic signals (primarily for f > 3 mHz)
- Astrophysical foreground (for f < 3 mHz large number of sources per frequency bin)

(Nelemans et al, 2001)
LISA Configuration
LISA Configuration

Round Trip time = 32 seconds
Three Arm Interferometer
Three Arm Interferometer

Proof Mass

Spacecraft A

Arm 1 ($l_1$)

Spacecraft C

Arm 2 ($l_2$)

Spacecraft B

Arm 3 ($l_3$)
Three Arm Interferometer

Proof Mass
Three Arm Interferometer

Proof Mass

Spacecraft A

Arm 1 (L1)

Spacecraft B

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Spacecraft C

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Arm 3 (L3)
Three Arm Interferometer

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Three Arm Interferometer

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Spacecraft B

Spacecraft C

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Three Arm Interferometer

Proof Mass

Spacecraft A

Spacecraft B

Spacecraft C

Arm 1 ($L_1$)

Arm 2 ($L_2$)

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Three Arm Interferometer

Proof Mass
Three Arm Interferometer

Proof Mass

Phase Difference

Spacecraft A

Spacecraft B

Spacecraft C

A1

A2

B1

C2

Arm 1 (L1)

Arm 2 (L2)

Arm 3 (L3)
Three Arm Interferometer

- **Proof Mass**
- **Spacecraft A**
  - Arm 1 ($L_1$)
  - Arm 2 ($L_2$)
- **Spacecraft B**
  - Arm 2 ($L_2$)
  - Arm 3 ($L_3$)
- **Spacecraft C**
  - C1
  - C2
- **Phase Difference**
Three Arm Interferometer

Proof Mass

Phase Difference
Sensing where it is
Spacecraft control
Spacecraft control
Spacecraft control
Spacecraft control
Spacecraft control
Spacecraft control
Spacecraft control
Spacecraft control
Spacecraft control

Solar Wind
Spacecraft control

Solar Wind
Spacecraft control

Solar Wind
LISA Instrumentation
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Problems at low frequencies
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- The LISA frequency range -0.1 to 100 milliHertz, is extremely unusual, technically. The timescales of these signals are minutes to hours- timescales on which:
  - Thermal changes occur
  - Mechanical relaxation happens
  - Environmental fluctuations occur
  - Thermal and gravitational feedback is possible
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  - Thermal changes occur
  - Mechanical relaxation happens
  - Environmental fluctuations occur
  - Thermal and gravitational feedback is possible

- Almost no laboratory test equipment has its performance accurately specified on these timescales
Laser Frequency Noise

![Graph showing frequency spectral density](image)

- **Unstabilized**
- **Stabilized**
- **Error-Point-Signal**
- **Shot-Noise-Limit**

Frequency Spectral Density (Hz/√Hz)

- 10^8
- 10^5
- 10^2
- 10^(-1)
- 10^(-4)

Frequency (Hz)

- 10^(-4)
- 10^(-2)
- 10^0
- 10^2
- 10^4
- 10^6

30 Hz/√Hz
Laser Frequency Noise

- Unstabilised lasers
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \sim 100$ kHz $/\sqrt{\text{Hz}}$. 
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \sim 100 \text{ kHz} /\sqrt{\text{Hz}}$
- Locked to a cavity on Friday, 4 September 2009
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \approx 100$ kHz /$\sqrt{\text{Hz}}$
- Locked to a cavity on the spacecraft
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \sim 100$ kHz /$\sqrt{\text{Hz}}$
- Locked to a cavity on the spacecraft $\Delta f \sim 30$ Hz /$\sqrt{\text{Hz}}$
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \sim 100 \text{ kHz} /\sqrt{\text{Hz}}$
- Locked to a cavity on the spacecraft $\Delta f \sim 30 \text{ Hz} /\sqrt{\text{Hz}}$
- LISA requires
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \sim 100 \text{ kHz} / \sqrt{\text{Hz}}$
- Locked to a cavity on the spacecraft $\Delta f \sim 30 \text{ Hz} / \sqrt{\text{Hz}}$
- LISA requires $\Delta f \sim 10^{-7} \text{ Hz} / \sqrt{\text{Hz}}$
Laser Frequency Noise

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UNLESS THE ARM
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \sim 100 \text{ kHz} / \sqrt{\text{Hz}}$
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UNLESS THE ARM LENGTHS ARE
Laser Frequency Noise

- Unstabilised lasers have $\Delta f \approx 100 \text{ kHz/}\sqrt{\text{Hz}}$
- Locked to a cavity on the spacecraft $\Delta f \approx 30 \text{ Hz/}\sqrt{\text{Hz}}$
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UNLESS THE ARM LENGTHS ARE EXACTLY EQUAL
Arm Locking
Arm Locking

• The accuracy with which a laser can be stabilised against an optical cavity goes as :
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\[ \frac{\lambda}{L} \]
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- The biggest optical cavity we have is the LISA arm itself
Arm Locking

- The accuracy with which a laser can be stabilised against an optical cavity goes as:
\[ \frac{\lambda}{L} \]
- The biggest optical cavity we have is the LISA arm itself
  \[ L \approx 5 \times 10^9 \text{ m} \]
Arm Locking

• The accuracy with which a laser can be stabilised against an optical cavity goes as:

\[
\frac{\Delta f}{L} \sim 10^{-4} \text{ Hz/\sqrt{Hz}}
\]

• The biggest optical cavity we have is the LISA arm itself

\[L \sim 5 \times 10^9 \text{ m}\]

This could achieve

\[\Delta f \sim 10^{-4} \text{ Hz/\sqrt{Hz}}\]
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• The biggest optical cavity we have is the LISA arm itself

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This could achieve \[ \Delta f \sim 10^{-4} \text{ Hz }/\text{root Hz} \]
Frequency noise effects
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Frequency noise effects

- For two equal arms, the phase difference, measured by a laser does not depend on the laser frequency at all.

- If the arms are unequal, frequency noise feeds into phase noise and therefore displacement noise.
Time Delay Interferometry
• We can artificially make the signal paths (arms) equal by using two routes
Time Delay Interferometry

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  - ABACA, and
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  - ABACACA, and
  - ACABA
Time Delay Interferometry

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  - ACABA

This is done by measuring the phase
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  - ACABA

This is done by measuring the phase with respect to an
We can artificially make the signal paths (arms) equal by using two routes:

- ABACA, and
- ACABA

This is done by measuring the phase with respect to an onboard clock at A.
Time Delay Interferometry

• We can artificially make the signal paths (arms) equal by using two routes
  - ABACA, and
  - ACABA

This is done by measuring the phase with respect to an onboard clock at different times on the outward and return paths.
• In fact there is a set of linear combinations of signals measured at different multiples of the light travel time that have useful properties.
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\[
\Delta ij = S_k(t - L_j) - S_i(t)
\]

\[
\Delta ij, kl = \Delta ij(t - L_k - L_l)
\]

\[
\gamma = \Delta ik - \Delta jk + \Delta kj, i - \Delta ki, j + \Delta ji, ki - \Delta ij, kj
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\[ \gamma = \Delta ik - \Delta jk + \Delta kj, i - \Delta ki, j + \Delta ji, ki - \Delta ij, kj \]

They all cancel the laser noise “completely” and have differing effects on the signal.
TDI

Symmetrized Sagnac

Sagnac

Michelson

log(h_eff)

log(f)
Can’t turn off the signal?
Window for SGWB
Unresolved WD Binaries

$N_{\text{tot}} = 1.5 \times 10^8$

$T = 1 \text{ yr}$
Can we do it?
Can we do it?

We need a 20 times improvement since 1887
Testing the idea

- LISA Pathfinder- launch 2011
Pathfinder - very different
LISA

• Exceptionally high quality science-
  – SMBH mergers at S/N of $10^3$
LISA

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• Might detect SGWB at $\Omega \sim 10^{-12}$
LISA

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  – SMBH mergers at S/N of $10^3$

• Technically demanding but well studied and developed

• Launch of LISA Pathfinder in 2011

• Launch of LISA 2020?

• Might detect SGWB at $\Omega \sim 10^{-12}$

• But this will depend on TDI and WD-WD binary spectrum
Gravity is talking
Gravity is talking
LISA will listen
Energy density of relic gravitational waves

$h_{r\text{ms}}(\nu)$ and $\Omega_{gw}(\nu)$ vs. Frequency $\nu$, Hz

- CMB anisotropies
- millisecond pulsars
- space-based interferometers
- ground-based interferometers
- high frequency g.w. detectors

$\Omega_{gw}, n = 1.2$

$\Omega_{gw}, n = 1.0$

Thermal, $T = 2 K$
Other mechanisms

Figure 4: A strongly first-order phase transition can produce a stochastic background of gravitational waves. The nucleated bubble walls expand at highly relativistic velocities and complete the transition to the true vacuum through violent collisions.

Bubble collisions  Decay of Cosmic Strings
V H F Detectors
V H F Detectors

- At frequencies of MegaHertz or GigaHertz, lasers cannot be used to trace gravitational tidal forces.
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• At Birmingham we are exploring the use of electromagnetic
V H F Detectors

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- At Birmingham we are exploring the use of electromagnetic interactions to signal the presence of gravitational waves.
Motivation for higher frequencies
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• No serious possibility of simple GR binary emission at these frequencies.
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- Possibly stochastic backgrounds around 10 GHz from early universe.
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Motivation for higher frequencies

• No serious possibility of simple GR binary emission at these frequencies.
• Possibly stochastic backgrounds around 10 GHz from early universe.
• Any possibility of a Hertz experiment (power $\sim f^6$) would require high frequencies.
• Higher dimensional theories predict radiation from the bulk at $f \sim (c/\text{curvature scale})$
Basic Principles

EM Field
Basic Principles
Basic Principles

EM Field

GW

Friday, 4 September 2009
Basic Principles

Induced EM modes of order $h \cdot \text{Field}$

EM Field

GW
Basic Principles

Induced EM modes of order $h\cdot \text{Field}$

Note that EM modes are easily detected using modern technology
Inverse Gertsenshtein Effect
Inverse Gertsenshtein Effect

- A long tube with a magnetic field across it
Inverse Gertsenshtein Effect

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Inverse Gertsenshtein Effect

- A long tube with a magnetic field across it
Inverse Gertsenshtein Effect

- A long tube with a magnetic field across it
- A GW passes down the tube, squeezing the magnetic field lines in and out
Inverse Gertsenshtein Effect

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Inverse Gertsenshtein Effect

- A long tube with a magnetic field across it
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- This “creates” an electromagnetic wave at the same frequency which can be detected
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Brane Oscillations
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- Many theories of gravity
Brane Oscillations

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- Many theories of gravity propose extra dimensions
Brane Oscillations

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- In an R-S universe a BH on
Brane Oscillations

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Brane Oscillations

- Many theories of gravity propose extra dimensions
- In an R-S universe a BH on one brane requires stabilisation by black string
Brane Oscillations

- Many theories of gravity propose extra dimensions
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- Predictions made by Seahra
Brane Oscillations

• Many theories of gravity propose extra dimensions
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• Predictions made by Seahra and Clarkson of the GW emission
Many theories of gravity propose extra dimensions.

In an R-S universe a BH on one brane requires stabilisation by black string.

Predictions made by Seahra and Clarkson of the GW emission due to the infall of a mass into the BH show high amplitudes.
Current Performance

Strain Sensitivity: August 2009: T=1 sec

Strain

F (Hz)
Best Extrapolation

Strain Sensitivity: August 2009: T=1 sec

B=12T, L=3m, T=20
This is a Source which exists!
This is a Source which exists!

But maybe in a universe which doesn’t
Best Extrapolation

B=12T, L=3m, T=20

Friday, 4 September 2009
Targets for $\Omega = 10^{-5}$

Level needed for $\Omega = 10^{-5}$
Level needed for $\Omega = 10^{-5}$
Stochastic Backgrounds?
Stochastic Backgrounds?

• At 10 GHz, to achieve \( \Omega=10^{-5} \), need to detect \( h=3.10^{-31} \).
Stochastic Backgrounds?

• At 10 GHz, to achieve $\Omega=10^{-5}$, need to detect $h=3.10^{-31}$.
• Best possible sensitivity at present seems to be $10^{-24}$ in one month.
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• Best possible sensitivity at present seems to be $10^{-24}$ in one month.

• However, detection techniques at these frequencies have not been well explored yet:
  – Direct conversion to EMW’s allows focusing of the signals from many collectors onto one detector
  – Heterodyne techniques could increase sensitivity very substantially
  – Magnet technology is improving
  – These systems are not expensive and not large
Conclusions
Conclusions

• LISA should be able to see SGWB’s at $\Omega=10^{-12}$ or so, but it will be 2020 before this happens.
Conclusions

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• LISA will access inflationary physics.
Conclusions

• LISA should be able to see SGWB’s at $\Omega = 10^{-12}$ or so, but it will be 2020 before this happens.
• LISA is a very high quality project.
• LISA will access inflationary physics.
• (This is at least 11 financial crises and two changes of government science policy away.)
Conclusions

• Current plans for VHF detectors cannot reach the nucleosynthesis limit and therefore may be irrelevant for SGWB studies.
Conclusions

• Current plans for VHF detectors cannot reach the nucleosynthesis limit and therefore may be irrelevant for SGWB studies.

• However,
  – They are at a very early stage of development and there are promising routes for improvement
  – They may already be sensitive enough to constrain higher dimensional models
  – They may access physics very close to the Planck Time